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Variation in the apparent density of human mandibular bone with age and dental status

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ABSTRACT

This study examines the variability in the anatomy of mandibles of differing ages and different stages of tooth loss. Mandibles from individuals between 19 and 96 y were sectioned into 2 mm thick vertical plane-parallel slices and cleaned of marrow and periosteum. The apparent density (mass per unit volume in g/ml) from midline (MID) and mental foramen region (MF) sites was determined by weighing the slices and dividing by a volume calculated as the product of section thickness and the mean area of the 2 sides of the section. The cortical thickness of the inferior border and the basal and alveolar bone heights were measured in radiographs of the slices. Mandibular apparent density was negatively correlated with the cross sectional area (midline $r = -0.48$, mental foramen $r = -0.45$), and at the midline was significantly greater in edentulous than in dentate individuals (means ($\pm$S.E.M.) edentulous n = 13: 1.43 ($\pm$0.07) g/ml; dentate n = 17: 1.27 ($\pm$0.04) g/ml, $P < 0.05$). Where a large enough age range was available, mandibular apparent bone density showed a significant increase with age (midline males: $r = 0.53$, n = 18) especially for dentate individuals ($r = 0.91$, n = 8). There was a correlation between the apparent densities at the two sites in the same mandible ($r = 0.64$), with the values obtained for the midline being significantly greater than for the mental foramen region (midline 1.34 ($\pm$0.04) g/ml; mental foramen 1.19 ($\pm$0.04) g/ml, $P < 0.001$, paired *t* test). The mandible shows great interindividual variability, but there may be a considerable reduction in cross sectional girth of the mandible following tooth loss, and, unlike postcranial sites, an increase in apparent density with age.

Key words: Ageing; osteoporosis; alveolar ridge.

INTRODUCTION

The mandible may undergo substantial remodelling following tooth loss. As we confirm here, there is great interindividual variation, with some people losing little bone and others having such extensive resorption that prosthetic rehabilitation or the placement of implants would be problematic. The extent to which osteoporosis in postcranial sites is related to changes in the mandible has been the subject of recent interest, but interpretation of the literature is complicated by the range of techniques which have been employed and the different variables investigated.

This paper studies the apparent density in thick, whole bone sections of the mandible and the changes that occur with ageing and tooth loss. It also assesses the value of the various radiographic measurements (e.g. cortical thickness and proportion of alveolar bone to total mandibular height) which are commonly used in studies of mandibular bone.

MATERIALS AND METHODS

Human mandibular material, representing 42 individuals, was collected from a variety of sources. Two specimens were collected postmortem, 10 specimens were from surgical resections and the remainder were from dissecting rooms (the cause of death was known).

Cleaning

All material was cleaned with an enzyme detergent solution at 40 °C (Terg-A-Zyme, Alconox, New York, USA; Boyde, 1984; Reid & Boyde, 1987). The soft tissue on the dissecting room material was resistant to digestion so the bones were first sectioned and washed

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> 100 h in running tap water (M Nimni, 1994, personal communication) before cleaning in frequent changes of Terg-A-Zyme solution (Alcanox Inc., NY, USA) for between 1 and 2 y. Despite this prolonged cleaning period, the contents of the inferior dental canal had to be carefully dissected out by hand.

Sectioning

The specimens were clamped in a specially constructed holder and were cut into 2 mm thick vertical slices using a low speed water-cooled diamond saw (Labcut 1010, DR Bennett Ltd, Leicester, UK) with minimal weight. The bones were oriented so that the cut took the shortest route across the cortex, which meant that large fragments had to be reclamped several times to allow for the curvature of the bone. The slices from the mandibular midline and 2–6 mm posterior to the mental foramen were selected for apparent density analysis. Slices which included part of the mental foramen itself were used for radiographic analysis. The midline site corresponds to that used by Lönberg (1951), Atwood (1963), Carlsson & Persson (1967) and Tallgren (1972). The mental foramen site has been used by many previous researchers (Parfitt, 1962; Carlsson & Persson 1967; de Aguiar et al. 1968; Atkinson & Woodhead, 1968; Wical & Swoope, 1974; von Wowern & Stoltze, 1977; Kribbs et al. 1983, 1989; Benson et al. 1991; Horner & Devlin, 1992; Hirai et al. 1993; Taguchi et al. 1995) and has become the 'standard site' for anatomical investigations of the mandible (von Wowern & Stoltze, 1979). All sections were cleaned, washed in distilled water, and dehydrated in ethanol.

Radiography

All radiographs were taken with the specimens lying directly upon the film packet. Before sectioning, the majority of the wet mandibles were radiographed on a custom-built microfocal x-ray unit with an effective spot size of 6–8 μm (Buckland-Wright, 1989; Buckland-Wright & Bradshaw, 1989) at a focus-film distance of 1 m, 50 kV, 150 mA and 0.02 s.

The interval between the highest point on the alveolar crest and the lowest point on the mandibular border was taken as a measure of the overall height of the mandible on a line passing through the mental foramen (Taguchi et al. 1995). The centre of the mental foramen was marked, as was the internal extent of the inferior mandibular cortex. Due to the indefinite transition between cortical and trabecular bone, the cortex was taken as having its limits where

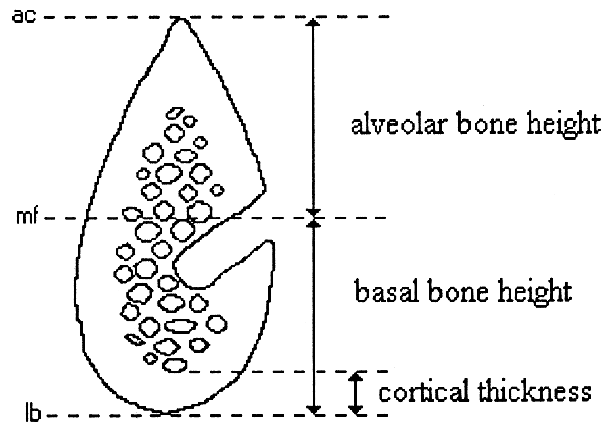

Fig. 1. Radiographic measurements at the mental foramen. The slices were laid flat on the film. Parallel lines were traced crossing the following landmarks: ac, alveolar crest; mf, midpoint of the mental foramen; lb, lower border of the mandible; internal surface of the lower border cortex. Following the literature, 'basal bone height' was taken as that from the lower border to the mental foramen, total mandibular height as that from the lower border to the alveolar crest, and 'alveolar bone height' as that from the mental foramen to the alveolar crest; almost needless to say, the latter can have nothing to do with the limits of bone which existed to support teeth. The cortical thickness of each slice at the lower border was also measured

the bone first appeared to be perforated. No attempt was made to correct for body or head size.

No equivalent measurement was made for the midline, because orientation of the curved fragments was difficult, the radiographic exposure required to penetrate the great volume of bone at the base of the midline caused 'burn out' at the alveolar crest, and because there is no clinically equivalent radiographic projection which allows for the examination of the full depth of the mandible in this region.

After sectioning, the slices were radiographed using a standard x-ray machine from 2 viewpoints: edge-on at 60 kV, 3 mA and 20 s and face-on at 50 kV, 3 mA and 20 s (see Fig. 1 for scheme of measuring points), in both cases using a 2 mm aluminium filter. Both radiographic projections were used in measurement of the thickness of the inferior mandibular cortex (Klemetti et al. 1994; Taguchi et al. 1995). The radiographs were placed on a light box and landmarks were traced onto tracing paper (Fig. 1). Intervals between the landmarks were measured with digital callipers to the nearest 0.5 mm.

Apparent density determination

The specimens and a millimetric scale were photographed on a tilting table using a 35 mm camera with an 80 mm macro lens. Two photographs were taken on both sides of every specimen at a tilt of 5° each side of the normal. These stereo-pair photographs were viewed using a Stereosketch (Hilger and Watts, UK) to allow the outline of the external surface of the cortex in each cut surface of the slices to be traced onto paper. This procedure allows the true 2-dimensional area within the envelope of each cut surface to be determined by active reference to the 3-dimensional image (Howell, 1980). After calibrating the mass per unit area of the paper, the mean cross sectional areas of the slices were then calculated from the mean weight of the cut-outs of the 2 sides.

The dried bone slices were maintained at room temperature: they were weighed on a pan balance (Sartørius, Göttingen, Germany) reading to 0.01 g, and reweighed over a period of days until a constant reading was obtained. Teeth, where present, were removed prior to weighing the slices. The volume for each slice was then calculated by multiplying the calculated area by the mean thickness of the slice as measured at 3 sites using digital callipers reading to 10 μm (Mitutoyo, Japan). It was then possible to calculate the true 'apparent' density of the specimens in g/ml. In addition, the mass per unit length of mandible was calculated for both sites by dividing the mass by the slice thickness.

Statistical analysis

The mandibular material was analysed for the effect of sex, age and dental status using Minitab (Minitab, Inc) statistical software.

For dental status, the mental foramen specimens were separated into completely dentate ('d' in figures), partially dentate ('p' – having anterior teeth and no more than 1 molar tooth) and edentate ('e'). Since the partially dentate group all had anterior teeth, the midline specimens were only separated into dentate and edentate classes, with no separate group for the partially dentate. On a few occasions, too little of a specimen was available to determine the number of teeth: these specimens were omitted from this aspect of the analysis.

The 2 sample t test was used to assess the differences between whole groups of data; Student's paired t test was used to reveal trends between different sites within a mandible; and Pearson's linear correlation coefficient was used in assessing the relationship of one variable to another, as well as for correlating between the measurements from the lateral and the anteroposterior radiographic projections. The r values are only given where $P < 0.05$. Data are given as the mean $\pm$ the standard error of the mean ($\pm$S.E.M.).

RESULTS

Quantitative observations

Mental foramen site

The age and sex details of the sample are as in Table 1. The males were significantly younger than the females ($P < 0.006$), but there was no difference in apparent density between the groups (Table 2), nor was there if the edentulous, partially dentate and dentate individuals were compared (means ($\pm$S.E.M.)): 1.29 ± 0.06 g/ml, n = 19; 1.26 ± 0.07 g/ml n = 10; 1.07 ± 0.05 g/ml, n = 7). The mean age for the dentate individuals (69 ± 5.33 y) was significantly lower than for the edentulous (81 ± 1.48 y) but not for the partially dentate (73 ± 3.91 y).

At the mental foramen site, there was no significant correlation between apparent density and age even when the sample was divided into edentate, partially dentate or dentate groups. If the measurement for the youngest male (35 y, 1.46 g/ml) is removed from the analysis, the male data show an increase in density with age (regression equation in range 48 y to 92 y is density $= 1.04 + 0.01 \times$ age, $r = 0.51$, n = 24). The section for this male came from a site slightly posterior to that used for the rest of the sample and included the socket for the mesial root of the lower first molar.

The cross-sectional area of the mandible reduced with age ($r = -0.50$) and with loss of the teeth. Edentulous and partially dentate mandibles were significantly smaller ($P < 0.001$ and 0.005) than dentate mandibles (mean areas $\pm$S.E.M.): 142 ± 16, 177 ± 10 and 258 ± 19 mm^2 respectively).

The correlation coefficient for measurements obtained from en face and lateral radiographs were: for

Table 1. *Number, age (in y) and sex distribution of specimens from the mental foramen*

	n	Mean	Median	S.E.M.	Range
All	42	74.9	78.0	2.0	35–96
Male	25	70.2	72.0	2.8	35–91
Female	17	80.7	82.0	2.2	56–96

Table 2. *Apparent densities of mental foramen site specimens (g/ml)*

	n	Mean	Median	S.E.M.	Range
All	42	1.23	1.17	0.04	0.81–1.77
Male	25	1.25	1.17	0.05	0.90–1.63
Female	17	1.22	1.17	0.06	0.81–1.77

Table 3. *Mean results from anteroposterior radiographic measurements* (*mm*)

	n	Mean	Median	S.E.M.	Range
Cortical thickness	37	3.5	4.0	0.2	1.5–5.0
Basal bone height	35	13.3	13.5	0.4	6.0–17.5
Whole bone height	37	23.5	26.0	1.3	6.5–34.5
Alveolar bone height	35	10.1	12.0	1.0	0.5–19.5

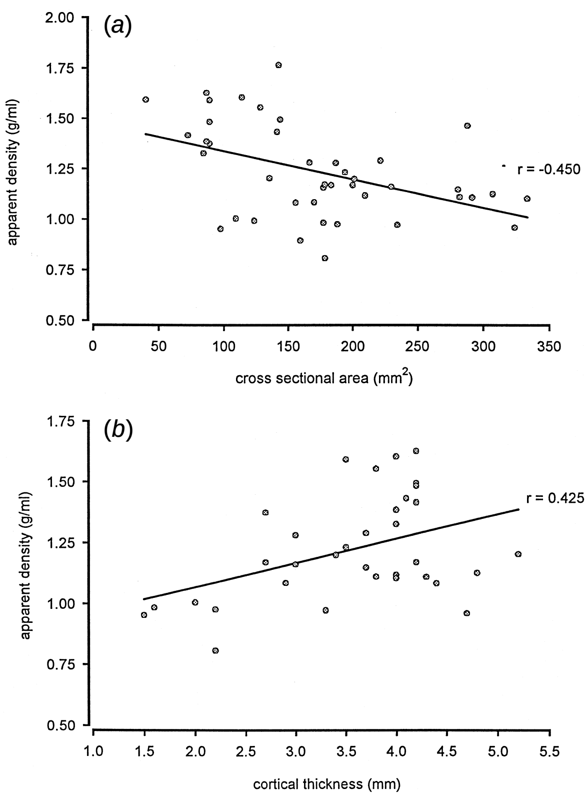

Fig. 2. (*a*) Apparent density against cross-sectional area for mental foramen site. (*b*) Apparent density against cortical thickness for mental foramen site.

cortical thickness $r = 0.79$, n = 17; for basal bone height $r = 0.79$, n = 15; and for total bone height $r = 0.99$, n = 17 (Table 3). The radiographic analysis was performed using the more reliable measurements obtained from face-on views (Fig. 1).

The radiographic measurements of bone height were all correlated: basal bone height with total bone height ($r = 0.81$); basal bone height with 'alveolar' bone height ($r = 0.64$); and total bone height with alveolar bone height ($r = 0.97$).

The graph for apparent density against area at the mental foramen site is shown in Figure 2*a*. The significant negative correlation ($r = -0.45$) could arise as the shrinking mandible is increasingly occupied by a relatively greater cortical bone fraction. The cortical thickness measurements showed a weak positive correlation with apparent density ($r = 0.43$; Fig. 2*b*), but showed no correlation with age, cross-sectional area, or the measures of mandibular bone height. However, there was a good correlation between cross-sectional area and the 3 measures of bone height (basal bone height $r = 0.74$, total bone height $r = 0.88$, alveolar bone height $r = 0.83$).

As would be expected from the above, there was a negative correlation between the apparent density and the 3 measures of bone height (basal bone height $r = -0.62$; total bone height $r = -0.64$; alveolar bone height $r = -0.59$), as there was with area as a whole.

MIDLINE SITE

Twenty eight individuals were examined. The details of the age and apparent density values are shown in Tables 4 and 5. The ages of the males and females differed significantly ($P < 0.05$), but there was no difference in the apparent densities.

There was a weak positive correlation between apparent density and age ($r = 0.53$) in males; there was a much narrower age range in the female group and no significant correlation was seen. The correlation between apparent density and age for males was good if only dentate individuals were analysed ($r = 0.91$). As with the mental foramen site, midline cross-sectional area decreased with increasing age ($r = -0.46$). Likewise, as it decreased, there was an increase in the apparent density ($r = -0.48$). However, there was no significant relationship between area and age when the sample was separated into dentate and edentate groups. The mean area for the

Table 4. *Number, age and sex distribution of midline mandibular specimens*

	n	Mean	Median	S.E.M.	Range
All	28	72.4	76.5	3.2	19–92
Male	18	67.7	73.0	4.5	19–86
Female	10	80.8	82.5	2.2	70–92

Table 5. *Apparent densities of midline specimens* (*g/ml*)

	n	Mean	Median	S.E.M.	Range
All	28	1.34	1.33	0.04	0.97–1.59
Male	18	1.39	1.35	0.06	1.03–1.91
Female	10	1.26	1.28	0.06	0.97–1.59

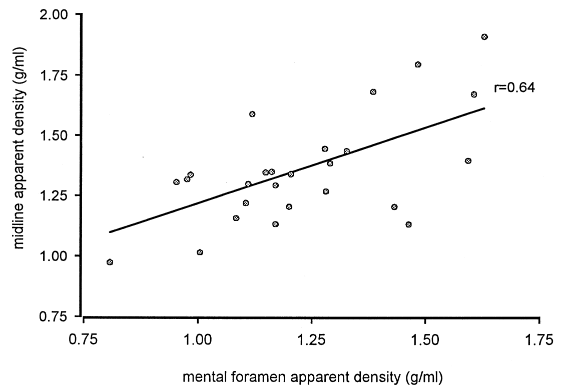

Fig. 3. Apparent density for mandibular midline against mental foramen site.

Table 6. *Mass per unit length* (*g*/*mm*)

	n	Mean	Median	S.E.M.	Range
Mental foramen	44	0.20	0.20	0.01	0.02–0.42
Midline	28	0.31	0.31	0.02	0.15–0.45

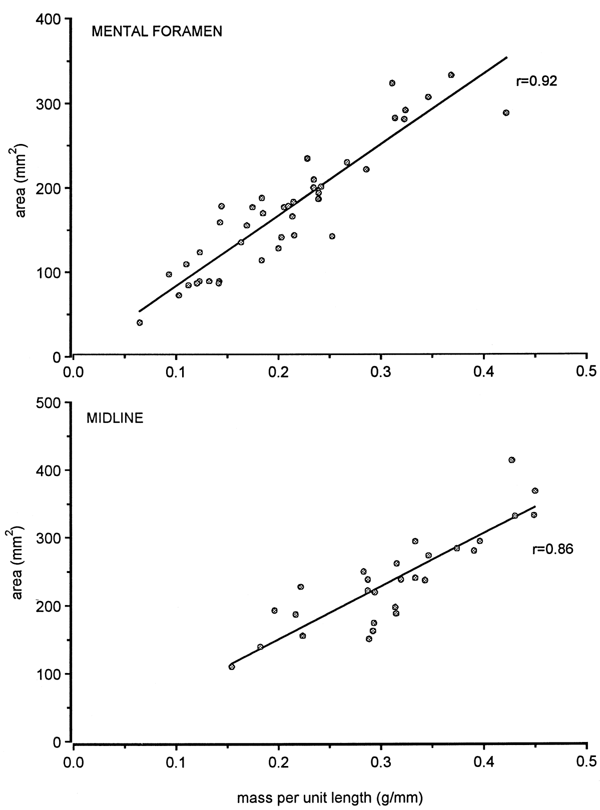

Fig. 4. Plots of area against mass per unit length.

dentate individuals was significantly greater ($P < 0.05$) than for the edentulous (means ($\pm$S.E.M.): 268 ± 16, n = 14; and 208 ± 19 mm², n = 14, respectively). There was no significant difference in mean age (dentate 66.79 ± 5.71 y; edentulous 77.93 ± 2.13 y).

The mean apparent density of the edentulous individuals was greater than that for dentate individuals (mean ($\pm$S.E.M.)): 1.43 ± 0.07, n = 13; 1.26 ± 0.04, n = 17 g/ml), but not to a statistically significant degree.

Comparing the sites within one mandible, there was a significant correlation between the apparent density at the mental foramen and the midline ($r = 0.64$, n = 28; Fig. 3) being greater at the midline (means ($\pm$S.E.M.)) mental foramen 1.19 ± 0.04; midline 1.34 ± 0.04 g/ml, $P < 0.001$ paired t test). The same was also true of area ($r = 0.87$; mental foramen 172 mm²; midline 230 mm², $P < 0.0001$).

The mass per unit length values for both the mental foramen and midline regions are shown in Table 6. A highly significant ($P \ll 0.0001$) correlation was found between the mass per unit length and the cross sectional area, both for the mental foramen ($r = 0.919$), and for the midline ($r = 0.864$; Fig. 4).

MORPHOLOGICAL OBSERVATIONS

Mental foramen site

The variation in size, shape and structure of the mandible is illustrated in Figure 5. Even from this small set, it can be seen how the apparent density of the bone was independent of area, height or size.

The location and condition of the inferior dental canal was variable. Trabecular thinning could be greater either below or above the canal (i.e. in the alveolar or in the basal bone). However, the superior portion of the medulla more frequently had smaller marrow spaces than inferior to the inferior dental canal with the occurrence of trabeculae apparently ending in free space being more common in the lower compartment.

Midline site

There was generally a much higher proportion of cortical to trabecular bone at the midline as was reflected in the apparent density measurements, but here the main bulk lay lingually rather than towards the lower border as occurred at the mental foramen site (Fig. 6). The labial cortex was often considerably more porous than the lingual (as was seen to a lesser degree at the mental foramen site, in agreement with Atkinson & Woodhead (1968), von Wowern & Stoltze (1980) and Jäger et al. (1990).

The trabeculae sometimes had a strong horizontal component, attaching slightly inferiorly on the labial side, and in some cases having a very ladder-like

Fig. 5. Photographs of 2 mm thick bone sections from mental foramen region of mandible. Age, sex, dental status (e = edentate, p = partially dentate, d = dentate) and apparent density (g/ml) from left: see opposite page.

arrangement (Fig. 7). In contrast to the mental foramen region, the marrow spaces were usually larger nearer to the alveolus than to the lower border.

At the level of the genial tubercles, there was frequently an extra thick strut of bone which sometimes spanned the full thickness of the medulla. In Figure 7 it can be seen that this was hollow and probably housed a neurovascular bundle, since it opened as a foramen on the lingual surface (Fig. 6, bottom right). Other foramina were frequently present, usually on the lingual, but occasionally on the buccal side.

In younger mandibles, the trabeculae existed as plates (Fig. 8, 9), but the marrow spaces enlarged with increasing age and finer, often disordered, trabeculae were seen. However, these did not always appear to have arisen through the remodelling of the preexisting trabeculae, and may represent sites of woven bone formation. Note the particularly exuberant example in the 70-y-old female (Fig. 10).

DISCUSSION

Density is, strictly defined, mass per unit volume. Many different meanings have accrued to this term in the bone field, and we use the term 'apparent density' to distinguish the term from histomorphometric or radiographic usage.

The midline and mental foramen regions selected for the present study are commonly used for studies of mandibular bone: they are fairly reproducible and are clinically highly relevant, since implants are often placed in the anterior portion of the mandible. Relatively thick sections of bone were used to give a good indication of the internal bony architecture and to prevent loss of trabeculae. This in turn dictated the need for a stereo observation method to determine the true area of the cut surface of the bone: here, we applied the method due to Howell (1980) for the first time in an anatomical study.

The decrease in the cross-sectional area with age seen at both the midline and the mental foramen sites is explained by increasing tooth loss. The present study illustrates the extent to which the girth of the mandible may change, yet the amount of bone tissue relative to the cross-section of the bone organ does not decrease: Figure 2*a* shows an increase in apparent density with decrease of cross-sectional area at the mental foramen site. At the midline the apparent density showed a clear increase even in dentate individuals. This did not merely reflect an increasing proportion of cortex as the bone became smaller: the bone becomes consolidated with increasing age. This should not be confused with any increase in porosity within mandibular cortical bone which is known to occur with age (Atkinson, 1969). This is in contrast to changes in bones of the postcranial skeleton most commonly affected by osteoporosis which usually do not change their external dimensions with age; thinning occurs internally.

Although the densities and total cross-sectional areas at the midline correlated with those from the mental foramen region of the same mandibles (Fig. 3), there are structural differences in the bone from the 2 sites (cf. Figs 5, 6). Thus in assessing the density of mandibular bone, one region of the mandible should not be considered in isolation. It is highly probable that there is a significant difference in the strain experience at the midline between dentate and partially dentate individuals. In support of this contention, Daegling et al. (1992) found the torsional rigidity of the mandible to change upon the loss of the teeth: this might have a secondary effect on what happens at the midline, one of the areas to experience the highest strains during function (Hylander, 1979; Korioth et al. 1992). Thus it is possible that the increase seen in the apparent density at the midline of the dentate males was influenced by the number of posterior teeth, which would tend to decrease with increasing age.

Convention regarding the relative distribution of bulks of bone in the mandible holds that basal bone is relatively permanent whilst the alveolar part may disappear with the loss of the teeth. The good correlation between the 3 measures of mandibular bone height (total bone height, basal bone height and alveolar height) shows that this is not true. Basal bone height would not correlate with alveolar bone height

Top row	86F(p) 1.43	85F(e) 1.20	74M(e) 1.63	79F(e) 1.42	83F(e) 1.59
Middle row	82F(e) 0.98	86F(e) 0.99	79M(e) 0.98	79M(p) 1.09	96F(e) 1.17
Bottom row	Scale (cm)	69M(e) 1.11	77F(e) 1.13	72M(d) 1.17	78F(p) 1.28

There is a great range in the cross sectional size even in edentulous mandibles (compare section at top right with that at bottom left). Trabecular quality seems to behave independently of the amount of cortical bone. The sections second from the left in the bottom and top rows have a large cross sectional area with a robust looking cortex but with sparse trabeculae. The section at the left of the middle row has a thinnish cortex but thick trabeculae. The section top right consists entirely of cortical bone. The location and condition of the inferior dental canal is variable; trabecular thinning may be more noticeable either below or above the inferior dental canal, however, the superior portion of the medulla more frequently has smaller marrow spaces than inferior to the canal with trabeculae apparently ending in free space being more common in the lower compartment. Scale in cm.

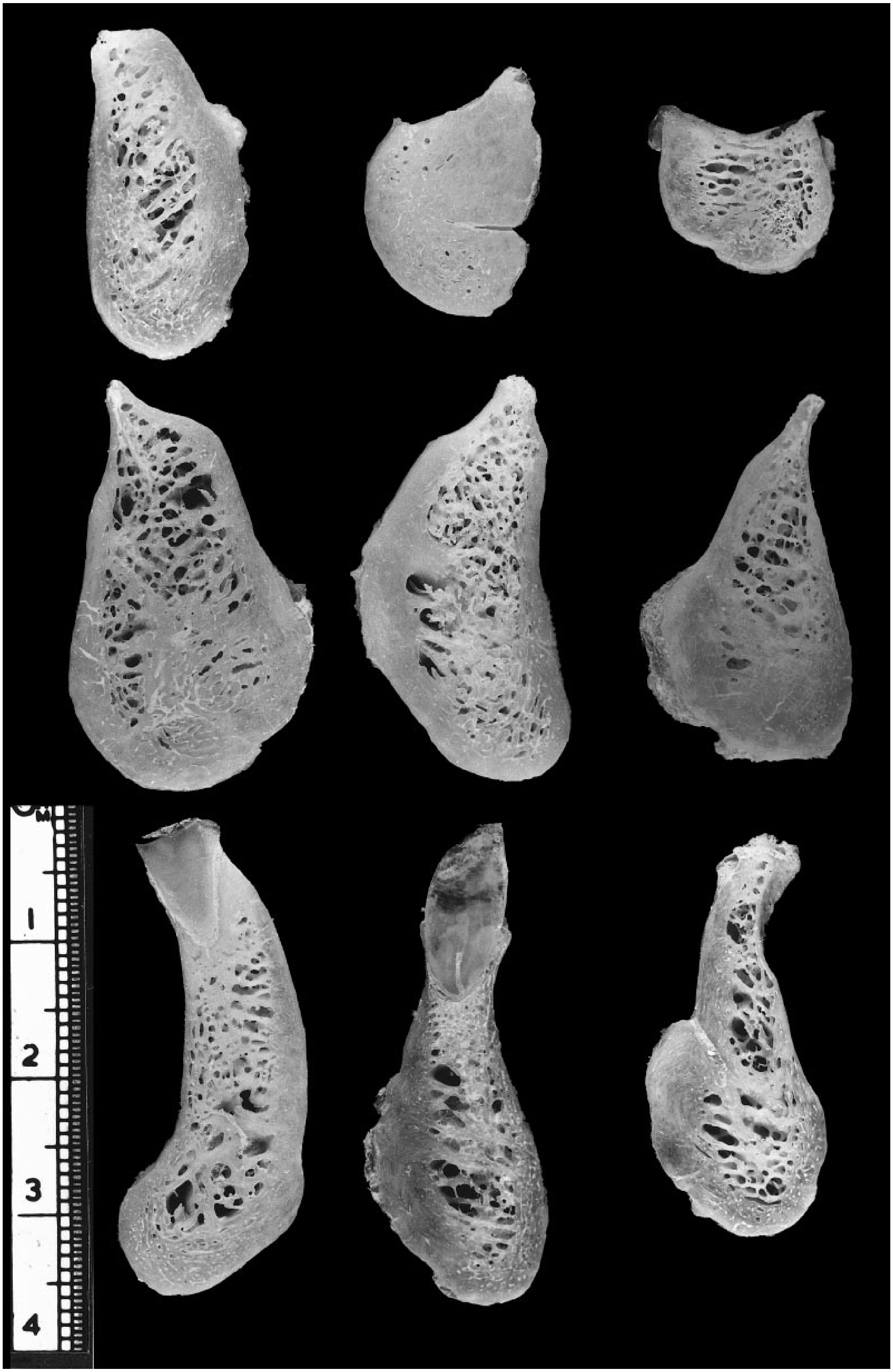

Fig. 6. Photographs of 2 mm thick sections from midline region of the mandible. Age, sex and apparent density (g/ml) for each individual from left to right is: see opposite page.

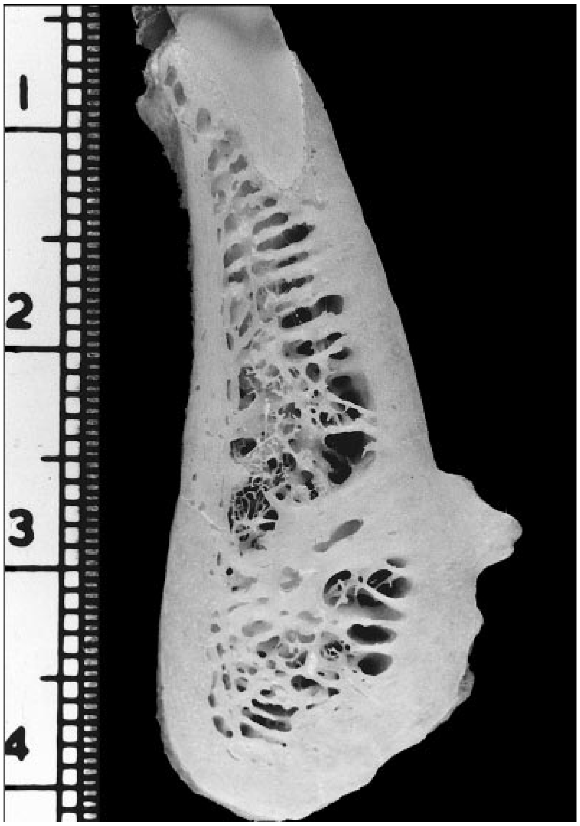

Fig. 7. Midline mandibular slice from 72-y-old male, showing: the strong directional component to the trabeculae which attach lower on the labial than on the lingual cortex; the large hollow strut (actually a mass of compact bone with Haversian canals) of bone opposite the genial tubercle; that the lingual alveolar bone may consist entirely of compact bone; and areas with extremely fine trabeculae (scale in cm).

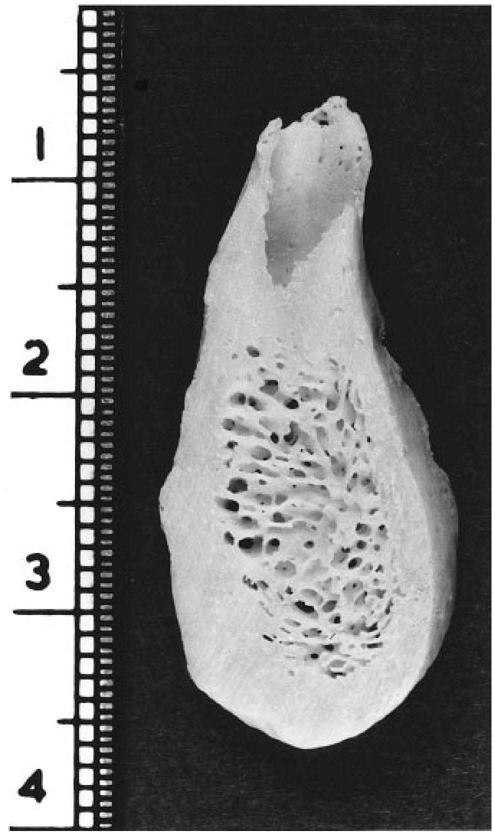

Fig. 8. Near midline slice from 35-y-old male showing the comparatively small marrow spaces and the socket surrounded by compact bone (cf. Fig. 9, scale in cm).

unless basal bone height also reduces after the loss of the teeth. In this case, basal bone is not immutable and it would not be possible to determine the original height of the alveolar bone at its prowess from measurements made in the aged edentulous mandible, yet several authors have done this following Wical & Swoope (1974). However, we do not feel that there are any sound means of determining where tooth supporting bone ends in the absence of teeth.

A highly significant correlation was found between the mass per unit length and the total cross-sectional area for both sites of the mandible (Fig. 4). This implies that the amount of bone in a cross section is dependent on the area of that cross section. The radiographic measures of mandibular height were found to be fairly reliable indicators of cross-sectional area. This implies that the mandible changes more in height than in width on becoming edentulous. However, there are differences in the labiolingual width of the mandible which might need to be taken into account when assessing information derived from lateral radiographic projections and dual photon absorptiometric bone mineral content determinations in cadaveric mandibles (Ulm et al. 1994): see the 2 examples at Figure 5 bottom centre which have the same height but contrasting widths.

Cortical thickness measurements have been used to assess the effect of osteoporosis on many bones, but even proponents of the use of this property say that it

Top row	82F(e) 1.34	74M(e) 1.91	83F(e) 1.40
Middle row	86F(p) 1.20	79M(e) 1.32	85F(p) 1.34
Bottom row	78F(e) 1.27	69M(e) 1.22	72M(d) 1.29

Note the morphological variation from those consisting almost entirely of compact bone to those having a greater trabecular component. In the midline of many mandibles a large strut of bone runs from the lingual downwards towards the labial cortex (see central slice): this usually contains a soft tissue bundle. In contrast to the mental foramen region, the marrow spaces are usually larger nearer to the alveolus than to the lower border (scale in cm).

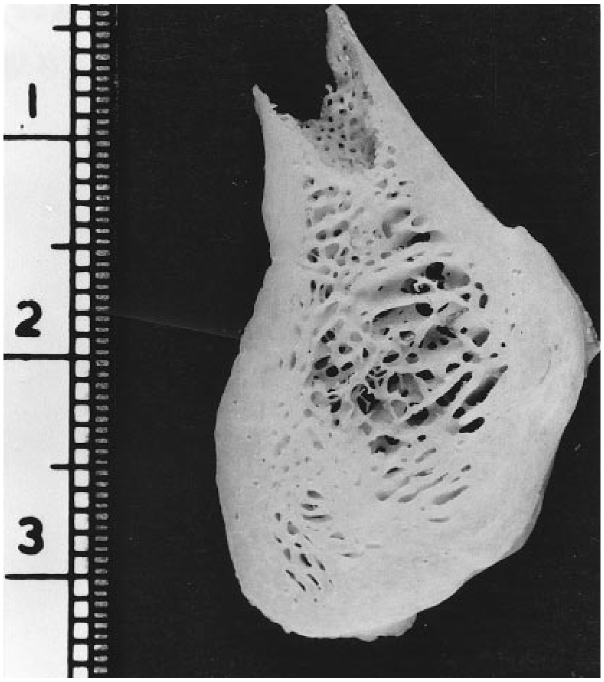

Fig. 9. Midline slice from 48-y-old male. Note the indistinct boundary between cortical and trabecular bone, and the perforated socket wall (scale in cm).

Fig. 10. Near midline slices from 70-y-old female mandible showing: the horizontal and downward component to the broad trabeculae in the superior part of the medullary cavity; the very many irregular small trabeculae (as described by Parfitt 1962); that the labial cortex is thinner than the lingual; and that the 'cribriform' plate of the tooth socket seems to consist almost entirely of compact bone (scale in cm).

should not be applied to the mandible (Garn et al. 1966). Nevertheless, several workers have shown an age related decrease in mandibular cortical thickness (von Wowern & Stoltze, 1979; Bras et al. 1982; Kribbs, 1990). In a study of over 350 patients, Klemetti et al. (1994) found that there is an association between the height and radiographic *quality* of the cortex with varying severities of osteoporosis, but that the sensitivity was so low that no indication of osteoporosis risk could be obtained on an individual basis. The results of the present study indicate that although it is not justifiable to measure x-ray films by hand to better than to the nearest 0.5 mm, cortical thickness might be reasonably determined from lateral radiographs *of cleaned, isolated bone*. Under the best possible circumstances, examining face-on radiographs of transverse sections of cadaver material, we show a weak association of radiographic cortical thickness with apparent density ($r = 0.43$ Fig. 2*b*), but showed no significant change with age.

Summary of findings

1. Whether teeth are present or not, and independent of the sex of the individual, the mandible shows great variability in size, shape and in the fraction of its volume occupied by bone.
2. The apparent density at the midline correlates with that at the mental foramen region but is greater, reflecting its different structure.
3. Unlike other bones, the mandible may show an increase in apparent density with age, implying that the mandible may not be suitable for evaluating osteoporotic (osteopenic) status.
4. Basal bone height was found to correlate with alveolar bone height; since the cross-sectional area of the mandible decreases after tooth loss, it is unsafe to assume that basal bone height is constant throughout adult life. It follows that it is not possible to use a measure of basal bone height in the aged, edentulous mandible to gauge the pre-extraction height of the alveolus, as has been done in previous studies.
5. We found no relationship between radiographic cortical thickness and age.

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APPENDIX

A note on cleaning bone from dissecting room material

Most of the material was obtained from dissecting rooms and therefore had been in fixative (made up of 12.5 l industrial methylated spirit, 2.5 l 80 % phenol solution, 1.5 l formalin and 3.0–3.5 l glycerine), which seemed to render the soft tissues much more resistant to the usual digestion methods. Many strategies for cleaning the soft tissue off bone have been described (Hall & Russell, 1933; Mahoney, 1966; Grayson, 1967; Boyde & Jones, 1974; Snyder et al. 1975; Boyde, 1984; Coy, 1987; Krüger, 1988; Wiltshire, 1989), but are either ineffective on phenol-formaldehyde fixed tissue or may damage the bone. Johan (1924) described a special 'antiformin' method using a hot solution of sodium carbonate and calcium hypochlorite with aqueous sodium or potassium hydroxide. This technique, however, can have a detrimental effect on the quality of the bone surface (Ivings, 1989), especially since some advocate that its use is followed by brushing with a medium wire brush (Chauhan, 1989). Johan's method may provide adequate results for the preparation of whole skeletons or bones for gross anatomical teaching purposes, but would not be suitable for study at a higher resolution. Furthermore, the strongly alkaline and heat conditions would probably render the bone partially anorganic. A variety of alternative cleaning techniques was therefore tried including: aqueous sodium hydroxide, hydrogen peroxide, and sodium hypochlorite (bleach). Consistently good results for dissecting room material were obtained using bleach (5% available chlorine diluted to 1:3 to 1:100, with or without sonication for 2–30 h); this removed little organic matrix within the bone, which thus did not become brittle. This technique was not adopted since making the specimen partially anorganic may affect the results to be obtained in a parallel study using quantitative backscattered electron analysis (Kingsmill & Boyde, 1998). The present study therefore selected the technique of prolonged washing followed by the use of an enzyme detergent solution.

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